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RADC, USAF ltr, 8 Aug 1973

AD824449

RADC-TR-67-420, Volume I
Final Report

ACCELERATED TESTING TECHNOLOGY

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Hughes Aircraft Company

TECHNICAL REPORT NO. RADC-TR-67-420
November 1967

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Rome Air Development Center
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FOREWORD

This final report was prepared by W. Yurkowsky, R.E. Schafer and J.M. Finkelstein of Hughes Aircraft Company, Ground Systems Group, Fullerton, California, under Contract AF30(602)-4046, project number 5519, task number 551902. Secondary report numbers FR 67-16-157, FR 67-16-185, reporting period covered February 1966 to July 1967. RADC project engineer Donald W. Fulton (EMERR).

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This report has been reviewed and is approved.

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ABSTRACT

This final report is a result of a study performed for RADC under Contract AF 30(602) -4046. The purpose of the study was to survey, document and report on the available methods of reducing reliability test times and test costs. The detailed results of this study have been, as required by the contract, produced in an "Accelerated Life Test Handbook." The methods of reducing test time/costs available are included in quite some step by step procedural detail in the "Handbook." For this reason, this final report is of somewhat a supplemental nature (to the "Handbook"). A serious reader of this report may well find the "Handbook" of interest also. The methods surveyed and written up as possibilities for reducing reliability testing time/costs were classified as:

1) Accelerated Life Test (ALT) Methods (electronic, electromechanical and mechanical parts).

   Important ALT's: Step stress tests, Invèrse power rule test, and Arrhenius and Eyring models.

2) More Powerful Statistical Methods

   Important Methods: Bayes tests, distribution free and distribution dependent tests.

Also considered is

3) The multiple modes of failure problem.

In this report each of the above three classifications is described in some detail with respect to

1) present state of art
2) recent advances
3) shortcomings and recommendations for future advancement.

It was found that while there has been a good deal of work written on the problem of reducing reliability test time/costs, only a fraction of it is of excellent quality and that more research is required particularly in the area of ALT validation and algorithms. In the area of Bayes methods, more work is required on prior distributions.

CONTENTS

EVALUATION

This study was addressed to an assessment of the state-of-the-art of methods applicable to reducing the time and expense associated with life testing for reliability purposes of parts employed in electronic systems.

The study has produced a Handbook of Accelerated Life Testing Methods which provides, in a compact and usable format, all that is useful and pertinent in reducing the time/expense of life testing through the use of over-stress techniques or more powerful statistical methods. A total of 524 documents were reviewed which resulted in the selection of 25 over-stress techniques and 33 more powerful statistical methods. The over-stress techniques were selected on the basis of the existence of an algorithm for converting lives at accelerated conditions to lives at accelerated conditions to lives at normal conditions, statistically sound validations of the algorithm, and a physical model explaining the algorithm. Had these criteria been rigidly applied, far fewer techniques would have been selected. The selection criteria applied to the more powerful statistical methods were that they either reduce test time/sample size for a given confidence, increase confidence without change in time/sample size or which offer savings in data analysis or testing. A further criterion, applied in the selection of these methods, was that they be "new" in the sense that a practicing engineer would not be expected to have knowledge of them. These methods fall into three general categories. The first allows the use of prior information based on Bayesian statistics. The second group is classified as distribution-dependent with the method based on order statistics. The last group is distribution-free, i.e., nonparametric. It is concluded, as a result of this study, that, quite in spite of voluminous literature, accelerated life testing for reliability purposes is in its infancy. What appears to be missing is a multidiscipline approach involving engineers, physicists and statisticians. The use of valid statistical methods must be encouraged and it is hoped that the inclusion of such methods in this handbook will prove a step in that direction.

DONALD W. FULTON
Reliability Engineering Section
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1.0 Introduction

1.1 The Reliability Testing Problem

As the design of a part is improved, its reliability becomes more difficult to demonstrate in a reasonable time with a realistic sample size and within an economic budget.

The increasing complexity of modern defense equipments makes it mandatory that the individual parts comprising them be highly reliable. If parts have an extremely long life expectancy the task of demonstrating this fact becomes increasingly difficult as reliability is improved. And yet it is important to know how long a part can be expected to carry out its mission before it is selected to perform an important function in a system.

This problem can be solved by gathering field performance information. However the system, equipments, and parts would all be obsolete before the answer was available. Parts can be tested in the laboratory under conditions which simulate actual use. But the exact reproduction of mission operating and environmental stresses is difficult to accomplish and again time and test expenses are deterring constraints. Sample sizes can be increased to reduce test times but this action increases test expenses at an extremely fast rate.

This report is devoted to an investigation into methods of solving the reliability testing problem through the use of accelerated testing methods. These are tests at stresses higher than nominal design levels applied either singly or in combinations at either constant, progressively increasing or increasing by steps, stress levels. It is not an objective of the study to develop new methods but it is to review the present state of the art of methods which have been developed and used for reducing test times, expenses and sample sizes.

In addition to a review of the research done in the field of ALT (accelerated life testing), the present state of the art has been evaluated in more powerful statistical methods of reducing test times and expenses. These methods fall generally into three categories. The first is the use of prior information. This is typified by the many methods developed using the theory of Bayesian statistics. A second approach is the use of distribution dependent methods. This group of methods is generally based on order statistics and has been used by McCool and others in estimating percentile points of the failure distributions of ball bearings. The third approach to reducing test times and expenses through the use of more powerful statistical methods is with distribution free methods. A typical example of these is the method of testing for increasing failure rate developed by Proschan.

Each group of methods for reducing test times and expenses has been searched out in the literature, evaluated, classified and placed under one cover in the Handbook of ALT Methods. Therefore hopefully one who is interested in reducing test times and expenses should be able to find all that is pertinent and useful on the subject in a central location in a compact and usable format.

While the Handbook of ALT Methods is meant to be a working document for the practicing test engineer, the objectives of this report are to present the methodology used in performing this study, to explain the evaluation systems used on the methods reported in the literature, to establish the criteria for the inclusion of a method in the Handbook, and to highlight the useful methods developed as well as those which show promise for future development.

To fulfill these objectives the first section of this report defines the reliability testing problem, defines an accelerated life test, outlines the study plan used and briefly describes the Handbook of ALT Methods.

Section 2 reviews the traditional accelerated life testing methods developed and used over the years. This includes a summary of the theory on which each method is based, its scope of application and the degree of success in its use. Each is described in terms of the engineering and statistical assumptions underlying the use of the method and in terms of its efficiency in yielding accurate results while meeting the goals of reducing test times and expenses. Specific treatment is given to step stress testing, the progressive stress testing, and the Arrhenius and Eyring Models. A subsection is also devoted to typical statistical methods presently being utilized for reducing test times and expenses.

Section 3 outlines recent advances in life testing and discusses the theories and methods which seem to offer the most promise in the solution of the reliability testing problem areas. Specifically the section is broken into ALT methods and statistical methods. The ALT methods subsection describes work sponsored by RADC in the use of various time transformations on the distributions of failure times at both accelerated and rated stress levels. A second advance is described in the use of regression models to develop response surfaces. This work has been sponsored by the US Army Electronics Command. Each method is described in terms of the theory underlying the method, the statistical models used for transforming results at accelerated stresses to results at rated stress levels, as well as the scope of utilization and degrees of validation developed thus far.

A third subject in this subsection advances the theory of multiple modes of failure as it relates to accelerated life testing. Briefly it investigates the assumption that when a part is first put into service, many failure mechanisms begin to attack it with the result that one of them eventually causes the failure of the part by means of a given failure mode. The failure analysis will indicate that the failure occurred from a single failure mechanism (i.e. the one that caused ultimate failure) but in truth all modes have caused a share of the damage. This theory results in a unique failure distribution whose characteristics were studied in detail. The latter part of Section 3 is a review of the more powerful statistical methods which can be developed into useful tools in the reduction of test times and expenses.

Section 4 summarizes the conclusions of the study while Section 5 outlines recommended areas for further useful research. Section 6 is a bibliography of all the literature that was reviewed in detail during the course of the study effort.

1.0 Introduction

1.2 Definition of ALT

An ALT is a test method based on sound engineering and statistical assumptions which utilizes a statistical model related to physical laws of failure to transform reliability information generated in a short time by an economical and accurate method to quantitative repeatable estimates of a part's reliability characteristics when it is operated at rated stress levels.

The definition of accelerated life testing given above is a lengthy, complex statement. This is so because the term being defined is characterized by many facets most of which are quite complex. More important, however, is the fact that all of the stated requirements that define an ALT must be considered before one can enjoy the benefits of reduced test times and expenses. None can be omitted or overlooked or the result will be subject to error. Errors in test results or in the actions taken as a consequence of the test results are usually costly and this cost must be included in the total cost of test programs. Therefore, the statements that follow elaborate the details of the ALT definition. They are based on a detailed analysis of the state of the art of accelerated life testing methods as reported in the literature.

Sound engineering assumptions are required in order to select the stresses and stress levels that will most likely result in the specification of a valid test method. Stresses that will not be experienced during actual use or which will change the physical state of the part's materials will not likely yield meaningful results.

Sound statistical assumptions will result in the production of accurate, efficient and above all adequate quantities of test information to allow one to make reasonably accurate inferences regarding generated results. One of the major statistical weaknesses encountered in the study of ALT literature was the specification of insufficient sample sizes. Another major problem was that full benefit was generally not taken of the synergistic effects afforded by the application of several stresses in combination to induce failures in shorter times. On the other hand, many researchers performed tests with combined stresses and yet made no attempt to test for the significance of interactions.

Other statistical requirements for valid ALT methods are that they should impart to the devices tested, a cumulative failure distribution that results in failure more quickly over a given range of test time than other potential ALT methods. Further, it should produce a hazard rate in the parts tested that is higher at all points over a given range of interest than that of parts operated at rated stress levels. The parts tested at accelerated stresses should be described by the same general family of failure distribution functions as parts tested at rated stresses. While this latter point is not an absolute necessity, it must be recognized that the mathematical difficulties of transforming between results displaying different families of failure distribution functions are not simple.

The literature of ALT is filled with test results based on the assumption of exponential failure times. Before a statistical extrapolation model can be utilized to transform accelerated test results to estimates of reliability at rated stresses it is necessary to

determine the validity of these assumed failure distributions at both high and normal stress levels. Frequently, the models used were simply not possible. For example, in References 90, 91, 92 and 233 an extrapolation model is used for solid tantalum capacitors which requires that the Weibull shape parameters of the failure distributions at both accelerated and rated stress levels must be equal. Yet empirical evidence is presented in these same references suggesting that the shape parameters are not equal. There are many other cases where a failure distribution was assumed and no attempt was made to validate the assumptions when empirical data was generated.

Physical laws of failure which explain the reason for the reduction of life due to severe stresses must be discovered to adequately explain the extrapolation models. Without them, it is easy to misinterpret test results brought about by the unrealistic activation of failure mechanisms not operating at rated stress levels.

The efficiency of an ALT method in yielding quantitative estimates of reliability is a point of major interest. Most ALT's are performed for the purpose of producing quantitative results in short times at severe stress levels which are translatable to estimates of life characteristics of the part at normal stresses. The demonstration of quantitative results requires a more correct and complete ALT method. If only comparative results are required a less stringent set of requirements for validation is needed but naturally the utility of the results are devalued.

The final aspect of ALT to complete the definition is that accelerating stresses should be selected which are easily applied, controlled and measured. In this same vein the test method should specify equipments that are economical and accurate. The literature on ALT is full of test results whose accuracy is questionable due to malfunctions of sophisticated test procedures and equipments. The collection of the data is best gathered by an automatic method if possible which will record the exact failure time.

The above definition and justifying discussion are aimed at the fulfillment of one of the principal objectives of the study. This was the development of a concise, accurate and durable definition of accelerated life testing that would reflect the efforts and experience of the entire body of ALT researchers.

An important feature of the research effort was a very complete search, analysis, and classification of the published information relating to the reduction of test times and expenses.

At the beginning of the present study effort the research team had in its possession a large number of publications on ALT as a result of related studies which had recently been completed. However the search was continued and remains a continuing effort. At the present time well over 500 articles related to all phases of the subject have be been located, classified and reviewed.

The most fruitful sources were the proceedings of the symposia of IEEE, AIAA, ASQC, IRE, and ASME etc. The Journal of the American Statistical Association, Technometrics and Industrial Quality Control also yielded many valuable contributions to the body of knowledge. Defense Documentation Center Lists, Hughes Company Document Indexes and many other reference sources provided valuable information. The current contributions to the literature were monitored with the aid of NASA Reliability Abstracts and Technical Reviews.

The articles upon review were classified as relating to general ALT problems, statistical methods of reducing test times and expenses. The general ALT methods articles dealt mostly with the results of various test programs carried out on specific parts. The articles on statistical methods were in general tutorial papers explaining the methodologies of correctly analyzing data which were generated in accelerated life tests. The works on more powerful statistical methods were those devoted to the goal of reducing test times and expenses by other than methods of accelerated life testing.

The general ALT papers were classified further by part type. Those on electronic and electromechanical parts were placed into one category while those on mechanical parts were treated separately.

Semiconductor devices, and film resistors, and capacitors were studied with the ALT method known as step stress testing. Capacitors of all varieties and other dielectric materials were popular parts for study in conjunction with the inverse power rule ALT method. Various semiconductor devices plus certain resistor types were frequently studied by means of parameter degradation models such as the Arrhenius and Eyring models. Relays and switches were tested and their results analyzed using models of time transformations on aspects of the failure distribution as well as with the aid of regression models in the form of response surfaces.

The literature on mechanical parts was less voluminous. The mechanical part which has been treated most successfully in the development of ALT methods is bearings. Numerous sources report on the utilization of Palmgren's equation for the estimation of mean life or some percentile of the life distribution for various bearing types and styles. Various manufacturers report differing values for the exponent in the equation

and these small differences are supported by the works of Lieblein and Zelen (Reference 218). The works of McCool (References 374 and 375) are significant methods for reducing test time by testing only to a predetermined number of failures.

Gears have been studied with a variation of the bearing equation and by a test utilizing "measured weakening" of the teeth by deliberate creation of cracks. O-rings, castings, airplanes, and parts for jet airplane engines are other mechanical parts on which ALT studies have been attempted.

The major point of interest in the study of any given ALT method was the determination of the degree of validation of the method for a given part or family of parts. In general no cases of complete validation were encountered. This was largely a function of the engineering and statistical assumptions made, deficiencies in the experimental designs, malfunctions of test equipments or simply the lack of sufficient funds to conclusively prove the worth or lack thereof of the method.

The most frequent statistical assumption made was that failure times of parts are distributed exponentially. Many of the statistical and physical models require this assumption in order to be valid. The statistics of the exponential assumption are appealing but frequently empirical results prove that this assumption is not applicable.

Sample size is frequently too small to yield results that are statistically significant. The use of small sample size is appealing in trying to develop an ALT because after all reducing sample size is a quick way of meeting one of the objectives of ALT - the reduction of test expenses. However it must be remembered that accurate results must be paid for with sufficiently large samples.

The sometimes complex test methods specified in an ALT do not enhance one's chances of obtaining accurate results. For example if one must frequently change temperature and other stress levels as in step stress testing or progressive stress testing, problems of control and rate of application can be troublesome.

The final aspect of the study method to be discussed is that of the range of applicability of ALT methods. In general certain methods or models indicate that the same method is useful for fairly large families or parts. For example the regression model used in References 128 and 166 appears applicable to different relay types. However different stresses, stress levels, and interactions of stresses are found useful in the reduction of test times. Different manufacturer's parts show promise in the use of time transformation functions in References 297 and 298 but different numerical inputs to the statistical model are required for each manufacturers parts.

1.4 The Handbook of ALT Methods

The Handbook of ALT Methods as the main product of this study, gathers under one cover the significant and promising contributions to the solution of the problem of reducing test times and expenses.

The volume of work that has been performed in the field of accelerated life testing is evidenced by the over 500 pieces of literature in the bibliography. Not all of these articles are of equal utility and certainly an engineer wishing to design a reliability demonstration test cannot be expected to become familiar with the entire spectrum of research in order to select the significant and useful methods developed for the solution of his specific problem.

Therefore it seems reasonable and timely that in order to advance the state of the art of economical demonstration test programs which can be performed in feasible time periods one must first establish the present state of the art.

To do this the study addressed itself to the problems of reviewing and evaluating the total effort in the development and use of ALT methods, classifying them as to application, and organizing them under one cover into a standard easy to use format.

The objective of putting the useful methods into a standard format was accomplished using the outline on the next page. In effect this makes the Handbook of ALT Methods a cookbook. The user should be able to find the part for which he seeks to design a test (if methods have been developed for it), determines the general details required of the test method in terms of equipment, stresses, stress levels and sample sizes. He can also quickly determine the degree of validation of the ALT method based on previous efforts. Results from other tests may be given to aid in gaining insight into expected results and test durations. A step by step instruction for implementing the method is presented. It contains all the equations and models required to convert test results at accelerated stress levels to estimates of part life at rated stresses. No references other than the handbook should be required to implement an ALT program on a given part. If the user of the handbook is interested in derivations or additional detail he is furnished with the reference from which the subject ALT method has been synopsized. Limitations warn the user of the weakenesses or risks of using methods not fully validated.

The handbook contains sections on improved validation methods, ALT methods for electronic and electromechanical parts, ALT methods for mechanical parts, Bayes plans for reducing test times and several other more powerful statistical methods.

The handbook gives an accurate assessment of advantages and disadvantages of the present available methods for reducing test times and expenses and presents in compact form the instructions for using the methods which represent the state of the art of accelerated life testing.

FORMAT FOR PRESENTATION OF AN ALT IN THE ALT HANDBOOK

Part Name and Description: Describe as fully as possible, i.e.: part number, manufacturer, nomenclature, rated loads, environmental ranges, material, size, application, etc.

Source: Publication(s) describing the method, author, date, source.

Purpose of Test: e.g., Compare parts, estimate MTBF, estimate Reliability, estimate failure distribution, etc.

Degree of Validation: Describe the methods used and the success of these methods in validating the usefulness of the mathematical and/or physical models.

Description of Test Method: Include definition of failure, details of equipment used in testing, methods of gathering data, method of application of accelerating environmental and/or operating stresses, sample sizes, etc.

Summary of Results: Describe mathematical and/or physical model used, analysis methods, and general summary of results at both accelerated and normal stress levels, include failure mode observed. Include a numerical example, if necessary, for clarity.

Instructions for Use: Give a step by step description of how to use the ALT method.

Limitations/Range of Applicability: Discuss any weaknesses of the method presented as to incomplete validation, questionable statistical or physical assumptions or use that can be made of the information presented. Name and describe the parts that can use this same ALT method.

References: List references that apply directly to the ALT method.

2.0 State of the Art of Life Testing

2.1 ALT Methods

2.1.1 CONSTANT STRESS TESTING

The most frequently used and most straightforward types of ALT methods in use are those with the stress or stresses applied at a constant rate.

Of the great volume of separate ALT efforts reported in the literature the majority of them were performed with the accelerating stresses applied at a constant rate. The simplest experiments were those performed using a single stress such as temperature or voltage applied at a fixed level or at several fixed levels. When the tests were performed at several levels a stress versus mean time to failure curve (S-N curve) can be prepared which is in effect a statistical model that can be useful for extrapolating to estimations of mean life at other stress levels (lower or higher). Whether or not extrapolation is possible depends on the maintenance of the same failure mode throughout the stress range. Although the same failure mode restriction is not absolute it would appear reasonable to assume that only time is being compressed in a over-stress test so long as no major changes are noted in the phenomena manifesting the failure.

An extension of the method of applying steady stresses is the use of more than one stress applied in combination. Experimental designs of this type (full factorial experiments) have been used in References 297 and 298 for relays, switches and O-rings. For relays three levels each of contact current, actuation rate, and ambient temperature were used as the accelerating stresses. In all, twenty-seven separate combinations of the stresses were tested in order to evaluate the effect on part life of each of the accelerating stresses as well as all the interactions of the stresses. The use of combined stresses frequently makes the accelerated test more efficient because the interactions may reduce life at a greater rate than the application of individual stresses.

Temperature, power, and voltage each at two levels were used in a full factorial experiment on semiconductor devices in Reference 246. Glass capacitors were tested with both voltage and temperature applied in combination in Reference 163. In both the above experiments the number of samples tested in each cell of the experiment were not constant, hence greatly increasing the complexity of the calculations.

If previous experience or engineering judgment suggests that certain interactions are not significant it is possible to reduce the total number of cells in the experiment. This omission of certain combinations of stresses is a fractional factorial design. A special variation of this known as a latin square design is often applied. The use of these methods reduce total test time since not all cells are tested but this is accomplished at the expense of information regarding certain of the interactions.

A variation of the fractional factorial experiment has been used with good success in the development of constant stress tests on several types of relays. The experimental procedure used is called a central composite design. It consists of a fractional factorial design supplemented with the testing of certain key stress combinations. The results of this type of constant stress test application are given in Refer-erences 128 and 238.

The constant stress type ALT methods are applied to test programs where the definition of part failure is either catastrophic malfunction or parameter drift beyond defined specifications. It has also been used where both failure definitions are applicable in the same test program.

When steady stress tests are employed there are two underlying assumptions that are desirable but not absolute necessities. The first is that the stresses should be selected at levels which will display the same general dominant failure modes. Locating these stress ranges sometimes involves additional preliminary experimentation prior to the main ALT program. The second desirable aspect to be sought is that the distribution of failure times at both accelerated and rated stresses should belong to the same general family of distribution functions.

Whenever possible, one of the stress levels included in a test program of this nature should be at rated levels. The inclusion of this information greatly simplifies the extrapolation problem. Naturally, it is usually quite difficult to generate data of this type since the excessive test times are precisely what the ALT's are attempting to eliminate.

In summarizing, it can be said that the advantages of constant stress ALT's are that one can construct the underlying distribution of failure times, it is possible to evaluate those stresses and interactions of stresses that significantly reduce test time and expenses and a typical S-N curve can be generated which relates stress and failure time. With conventional information such as this the development of a model relating expected life at all stress levels should be possible.

The disadvantages of constant stress tests are that the failure times at moderate and mild stress levels tend to be extremely long. Directly related to this is the fact that if the dispersion of failure times is large within a given stress level it might be possible to have either very short or very long failure times in a sample of parts on test. At high stress levels such as voltage or temperature the initial failures might occur almost instantaneously. On the other hand, a single part from a large sample might last an inordinately long time unless censoring of some type is employed. Another disadvantage is that if one does not have experience with a specific part of interest it might be necessary to utilize exploratory tests to determine the most logical stress levels to use to maintain the desired failure mode.

The final analysis of the above points leads to the conclusion that the most accurate work with the greatest degree of validation has come from constant stress tests. This is especially true where quantitative reliability estimates are required.

2.0 State of the Art of Life Testing
2.1 ALT Methods

2.1.2 STEP STRESS TESTING

Step stress testing has been used most successfully on ALT methods where the objective of the test is the determination of stress levels where failure modes change and where qualitative differences between lots are to be evaluated.

Step stress testing was developed for use on electronic parts by Dodson and Howard of Bell Telephone Laboratories. The methodology was based on work by Marcel Prot in the fatigue testing of materials.

It has been used on a great many different part types with many different objectives. Of all of this effort, it appears that the most successful efforts have been in the determination of the stress level at which failure modes change and in comparing qualitatively if a new design improves reliability over a current one. Additional problems solved are in the selection of the best part from among several choices based on qualitative evaluations. All semiconductor devices, film resistors and capacitors are the parts generally tested by this method.

The test method consists of placing a sample of parts on test at a relatively mild stress level for a fixed time period. At the end of this period the parts are checked for failure (either drift or catastrophic) and the parts which have not failed are put back on test at the next higher stress level. There they are tested for the same time period and the procedure is repeated until either a desired percentile or the total sample of parts fails. Voltage, temperature and the length of the time interval of stress application are frequently used variables in the test program.

The method of step stress testing is based on several important assumptions:

1) The S-N curve can be transformed into a straight line by some mathematical transformation representing a physical model. Usually, the transformation is logarithmic on the time scale and the reciprocal of the absolute temperature on the stress scale.

2) The failure times at any point on the S-N curve must be normally distributed with equal variance.

3) The transformed S-N curve represents the effects on life of a single failure mechanism or at least on a very dominant failure mechanism.

4) The variation in the failure times at any given stress level is due only to differences in the device under test.

5) The probability of failure at any given point in the stress-time domain is independent of how a part arrives at that point.

6) The identical S-N curve can be obtained either by constant stress tests at several different stress levels or by step stress tests at different time intervals where it is assumed that time is held constant as the stress is increased.

References 95, 96 and 97 are examples of the use of this test procedure on transistors and diodes. Storage temperature was used as the accelerating stress. Constant stress test results were compared with the step stress results and appeared to give results that were in general agreement. However, the complicated procedure of raising the temperature of the sample parts, holding them for a fixed time interval, cooling them to room temperature, measuring several operating parameters and then repeating the procedure appears to result in a more complicated and time consuming procedure than constant stress tests at most of the intervals where results could be compared.

Step stress tests on resistors, capacitors, transistors and diodes were performed extensively as reported in References 32 through 36 and 174. The criteria for failure were degradation of various operating parameters as stresses were increased. No failure times were recorded. Several combinations of step stress and constant stress tests were attempted in the hope of developing quantitative results but in general the most useful outcomes were qualitative and validation was never attained.

The advantages of this method of testing are that it does solve the problem of extremely short failure times and extremely long failure times, as well as pinpointint the stress ranges for given failure modes. The method is useful for qualitative comparisons.

The major disadvantage of step stress testing is that it has not been proven valid for making quantitative reliability estimates. Also excessive detail, control, and time are required in the tedious tasks of test performance and monitoring. In addition to the above, the exact failure time is not available but only the approximate stress level at which failure occurs. Exploratory tests must be performed to discover the stress level or time interval to use in the test program in order to obtain results in a reasonable time.

The major value of this type of test is in the qualitative assessment of reliability. It has been used in conjunction with the Arrhenius and Eyring models but again validation has not been successful at least as far as the limits of the literature reviewed for this report.

2.1.3 PROGRESSIVE STRESS TESTING

Progressive stress testing has been employed mainly in ALT methods for capacitors in conjunction with the inverse power rule as a statistical model but has not been proven valid.

Progressive stress testing is very similar to step stress testing in the theory and principles of application. Whereas, in step stress testing the accelerating stress is applied in increasing increments of stress for fixed time periods until a given fraction of the sample has failed, progressive stress tests are featured by an accelerating stress that begins increasing from some low value at time t=0 and rises at a continuous rate throughout the duration of the test. In effect then, it may be said that a progressive stress test is really a special form of step stress test in which the time duration of each step approaches zero.

With the similarities noted above one would suspect that progressive stress tests would be used in exactly the same applications as step stress tests. This is, however, not the case. Step stress tests have been attempted on most types of electronic parts but the use of progressive stress testing has been generally restricted to capacitors. Their use on capacitors has been in an attempt to reduce test times experienced in constant stress tests where the inverse power law is thought to be the statistical failure model for transforming test results at accelerated stresses to estimates of reliability characteristics at rated (or less severe) stress levels.

The assumptions in the inverse power rule when tests are performed at constant stress are that at a fixed temperature and given chemical state the total accumulated damage was defined by the following relationship:

$$\text{Total accumulated damage} = C\int_0^T \left[V(t)\right]^n dt$$

where

$V(t)$ = voltage applied at time t

n = power exponent of the inverse power rule

C = a constant

The above formula for the case of constant voltage stress becomes

$$\text{Steady Stress Damage} = CV_s^n T$$

For the case of progressive voltage stress, it becomes:

$$\text{Progressive Stress Damage to Time } T = \frac{C\lambda^n T^{n+1}}{n+1}$$

where

λ = uniform rate of rise of voltage from 0 in volts/unit time.

The working hypothesis then theorizes that damage to time T at constant and progressive stress are related by setting the latter two formulas equal to each other. The C's cancel out and the following relationship results:

$$T = \frac{\lambda^n \tau^{n+1}}{V_s^n \ (n+1)}$$

The use of this model as the inverse power rule then says that an equivalent steady stress failure time T at constant voltage V_s can be estimated from any progressive stress test with voltage uniformly increased at the rate λ using progressive stress failure time τ if n is known.

The problem of solving for n and verifying its constancy over a given range of voltages has been the subject of numerous research studies. Endicott, Hatch and Sohmer used this theory and method for mica capacitors. Their results are in Reference 111. They used data previously generated and hence were handicapped probably due to experimental error; however, they did develop useful knowledge. For example, prior to their work, everyone was using the progressive stress model with the assumption of an exponential distribution of failure times resulting from both constant stress and progressive stress tests. Their work clearly indicated that if failure times at constant stress were exponentially distributed then this created the requirement that in order for the progressive stress model to be applicable the results from a progressive stress test must be distributed according to the Weibull distribution with a shape parameter of n+1 where n is the power exponent of the inverse power rule. Schafer showed in the Handbook of ALT Methods that in addition to the above requirement on the Weibull distribution shape parameter, the scale parameter from progressive test times must have the value

$$\left[\frac{V^n(n+1)}{\lambda^n}\right]^{-\frac{1}{n+1}}$$

Kimmel (Reference 190) in 1958 used this ALT method on paper capacitors. He performed only progressive stress tests, assumed values of the power exponent and attempted to equate the results of two tests performed at different rates of stress increase. His results did not support the theory that this model was valid but were valuable in his development of anlysis methods. Many others have contributed work to attempt the validation of progressive stress tests but none have proven the model or method yield accurate results when test times are reduced in this manner.

The main advantage in the use of progressive stress tests is that they do eliminate the analysis problems caused by early and late failures in a test sample. However, there has, as yet, been no conclusive proof that the test method yields valid results when used in conjunction with the inverse power rule. Another extremely important drawback in the method is that very accurate controls are required to control the rate of increase of the stress or unreliable results will be the results.

2.1.4 ARRHENIUS AND EYRING MODELS

The Arrhenius and Eyring Models are physical models which have been studied frequently in attempts to explain the degradation of parameters of electronic parts due to environmental stress. No cases of validation of the models for ALT methods are known.

The Arrhenius Model was developed in the 1880's as the law which describes the reaction rates of chemical processes. Its adoption as an aid in solving ALT problems came about because of very logical reasons. The researchers in the field of ALT methods experimented by performing tests and then attempted to explain these empirical results in physical terms. The need for a physical explanation of empirical results is of paramount importance in the complete validation of an ALT method. In many of the simple electronic parts, it is easy to theorize that the mechanisms leading to degradation and failure are chemical processes and elevated temperature is frequently selected as an accelerating stress. Hence it seemed a natural course of events to attempt to apply this as a useful adjunct to the state of the art of ALT.

The Arrhenius Model as applied to ALT methodology assumes that the degradation of some performance parameter is linear with time with the rate of degradation depending on the severity of the accelerating stress. It further assumes that the logarithm of the degradation rate is a linear function of the reciprocal of the absolute temperature. Therefore, the following formula is used to relate observed test time at accelerated stress levels to equivalent time at rated stresses:

$$t = e^{-B(1/T' - 1/T)} t'$$

where

t = equivalent life at rated temperature

t' = observed life at accelerated temperature

B = an empirical constant

T' = accelerated test temperature in ^{o}K

T = rated operating temperature in ^{o}K

The basic procedure for performing an ALT using the Arrhenius Model is to find an operating parameter of the part of interest that displays a linear rate of degradation with time. If none of the operating parameters change linearly, it is often possible to obtain linearity with either logarithmic, square root, or other transformations of the data. It is also frequent that the ratio of the change of the parameter to its initial value will plot as a straight line with time. When a parameter has been found that changes linearly, tests are performed at several different stress levels and the slopes of the various degradation lines are found. These slopes are then used to make an Arrhenius plot - a plot of degradation rates versus the reciprocal of the absolute

temperature. If the points on this plot can be observed to display linearity then "true acceleration" is said to exist and the model is deemed representative of the physical laws of failure occurring to cause failure.

The use of the Arrhenius Model has been attempted in conjunction with results generated on several types of electronic parts. It has been fitted to results of tests where stresses were applied at constant rates, increasing rates and in step stress tests. While there are no cases of complete validation on record, some promising results have been observed.

The major complaint against proof that the model fits lies in the fact that usually not enough points are available for testing for "true acceleration" with the Arrhenius Plot. In fact, it would appear that most of the researchers in the field have selected three levels of accelerating stress to perform their studies. Reference 328 suggests at least five levels as the logical minimum. When the entire foundation of the validity of the model is based on an assumption of linearity it seems impractical to attempt to prove that in fact the data fit a straight line when only three points are available.

From the preceding paragraph, it would seem that the major shortcomings in the study of the use of the Arrhenius and Eyring Models is based on an insufficient number of stress levels. However, there are other arguments that strongly suggest reasons for the lack of validation that is evident. The use of the model is such that if one observes the failure times distributed exponentially at severe stress levels, the same distribution must characterize failure times at rated stresses. If on the other hand the accelerated stress failure times are distributed according to the Weibull then the rated stress failure times must also be Weibull with the same shape parameter. Observations of much data on electronic, electromechanical and mechanical parts yields very few cases where failure times are distributed exponentially but more importantly it is very uncommon to see data that is Weibull at different stress levels that yield the same shape parameter. The available empirical results simply make it very improbable that these models represent the degradation occurring in accelerated life tests.

The previous discussion has alluded mostly to the Arrhenius Model. The Eyring Model is another reaction rate equation that has been studied in ALT situations where the Arrhenius Model was found deficient. However, the same degree of success has been attained in applying it to ALT methods as has been experienced with the Arrhenius Model.

The statistical state of the art of life testing is well represented by MIL-STD-781A.

It will perhaps always be an open question as to what is the state of the art in statistical life testing. For example, one finds (a few) people far more advanced in their life testing procedures than the test plans of MIL-STD-781A. On the other hand, there are (too many) people who still are not familiar with MIL-STD-781A. In any event, a fair assumption seems to be that in life test applications MIL-STD-781A reasonably represents the state of the art.

The plans of MIL-STD-781A generally use sequential life test methods based on the assumption of exponential failure times and the accept/reject lines are determined so that

$$P(\text{Rejection} \mid \theta_0) = \alpha = \text{consumer's risk}$$

$$P(\text{Acceptance} \mid \theta_1) = \beta = \text{producer's risk}$$

where α β are both small and θ_0 is an acceptable MTBF and θ_1 is an unacceptable MTBF ($\theta_0 > \theta_1$). Within the framework of the criteria (α, β, θ_0, θ_1) and the exponential assumption the sequential procedures of MIL-STD-781A are about as good as one can do.

The key features of the MIL-STD-781A plans are

1) the assumption of exponential failure times

2) the criteria (α, β, θ_0, θ_1).

The statistical methods given in the handbook are not intended to replace MIL-STD-781A procedures in any way but to supplement them (particularly at the part level) when one or both of the above assumptions is invalid. For example, if part failure times turn out to be Weibull for a particular part then assumption 1 above is invalid and one or more of the methods of the handbook which assume a Weibull distribution may be used. Often the producer/consumer team desires different criteria for testing than the 4 tuple (α, β, θ_0, θ_1) for example, costs are sometimes desired as criteria. The Bayes plans of the handbook furnish such test plans. The Bayes plans also furnish tests based on other criteria.

In summary, then, the statistical methods are a supplement to MIL-STD-781A (particularly at the part level) not a replacement for it.

3.0 Advances in Life Testing
3.1 ALT Methods

3.1.1 TIME TRANSFORMATION MODELS

One of the shortcomings of current ALT practices is the frequent absence of an algorithm to relate "results" at accelerated conditions to those expected at normal conditions. Time Transformation Models are a method of overcoming this problem.

The usual ALT algorithm, if present at all, is a type of S-N curve. That is, some parameter of the failure distribution (e.g., median life) is functionally (usually graphically) related to stress level. This provides an easy means of converting life parameters from one stress level to another by testing at only one of the levels. Unfortunately, this procedure often provides little insight into the physical aspects of the problem (e.g., failure modes/mechanisms) and it provides little insight into whether or not the functional relationship can be expected to persist. In particular, regression methods are often used to fit these curves and the regression methods often involve assumptions which are improbable. In short, it is imperative in developing ALT methods to look not just at the parameters of the failure distributions but also the (form of) failure distributions themselves. As a matter of fact, the form of the failure distribution (at normal and accelerated conditions) not only has a great deal to do with the conversion algorithm, but (see Section 2.0 of the Handbook of ALT Methods) can be of great assistance in determining the validity of proposed physical models.

Time transformation models (TTF) are obtained from the mathematical relation between the cumulative distribution functions (d.f.) at normal and accelerated conditions. They are covered in some detail in references 388, 350 and 297. A time transformation function (TTF) is a function g (t) such that

$$F_A(t) = F_N[g(t)] \tag{1}$$

If F_A and F_N are continuous as is usually assumed then there always exists such a g(t). An example casts a great deal of light on the TTF:

First, suppose both F_A and F_N are exponential

$$F_N(t) = 1 - e^{-t/\theta_N}$$

$$F_A(t) = 1 - e^{-t/\theta_A} \qquad t,\ \theta_A,\ \theta_N > 0 \tag{2}$$

and presumably $\theta_A < \theta_N$. In any case, using Equation (1)

$$1 - e^{-t/\theta_N} = 1 - e^{-g(t)/\theta_A}$$

so that

$$g(t) = \frac{\theta_A}{\theta_N}\, t \tag{3}$$

Now, suppose failure time under normal conditions is denoted by t and it is assumed that time under accelerated conditions (t^*) is given by a particular linear transformation on t, say ct. That is, it is being assumed

time under accelerated conditions = $t^* = ct$.

Suppose further

$$F_N(t) = 1 - e^{-t/\theta_N}$$

making the change of variable $t^* = ct$ one obtains

$$F(t^*) = 1 - e^{-t^*/c\theta_N} \qquad (4)$$

Thus, time under accelerated conditions is also exponential with mean $c\theta_N$.

Now setting

$$\theta_A = c\theta_N$$

then

$$c = \frac{\theta_A}{\theta_N}$$

and

$$g(t) = ct \qquad (5)$$

For this example, it can be seen that

1) $g(t)$ is the function which relates time under accelerated conditions to time at normal conditions

2) $g(t)$ involves (see Equation 3) the parameters of both distribution functions.

3) If F_A and F_N are both exponential $g(t)$ must be $\theta_A/\theta_N t$

4) If one of F_A and F_N is exponential and a simple linear relation between accelerated and normal times is postulated then the other must be exponential and the constant of the transformation must be θ_A/θ_N.

Referring to 2) above $g(t)$ will always involve the parameters of the two d.f.'s F_A and F_N. Hence, a method of estimating $g(t)$ is available once having estimated F_A and F_N and hence, a method is available to estimate θ_N from θ_A (without additional future testing). Remarks 1), 3) and 4) above, provide ample basis for checking assumptions about physical models.

References 388 and 297 provide much more detail on TTF's. In general, they provide means of estimating parameters and failure distributions at normal conditions from accelerated tests and provide means of checking physical models.

3.0 Advances in Life Testing

3.1 ALT Methods

3.1.2 REGRESSION MODELS

The use of regression models in the development of ALT methods for relays appears to be a distinct improvement over previously employed conventional methods.

Through the years many researchers have employed various models, failure theories and test methods on many types of parts in order to attempt to empirically develop valid ALT methods.

Recently test results employing another method have been published on work performed on newly designed relays. The study efforts have been sponsored by the U.S. Army Electronics Command at Fort Monmouth, New Jersey. These results appear in References 128, 166, and 238.

The method consists of testing relays to failure using from three to five accelerating stresses applied simultaneously. The failure times generated are used to estimate the Weibull shape and scale parameters for each combination of stress levels. The experimental design used for determining the stress levels to be used in the overall program is known as a central composite design. The details of its development are given in "Design and Analysis of Industrial Experiments" by O. L. Davies.

Basically, a central composite design consists of a factorial design supplemented by certain well selected stress combinations that yield estimates of quadratic effects. The basic factorial can be either a full or fractional design. The stress combinations are selected in a manner which will allow the estimation of all main effects as well as all first order interactions. Higher order interactions are assumed to be non-significant in their effect on part life.

The estimates of the Weibull shape and scale parameters for each combination of stresses are used to develop a regression equation representing the appropriate response surface. For relays the accelerating stresses used were contact current, actuation rate, and ambient temperature. For a three factor central composite design, fifteen test cells of ten parts each were tested Regression equations of the form

$$Y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2$$

$$+ b_{13}x_1x_3 + b_{23}x_2x_3$$

were developed from the estimates of the various Weibull parameters. In the above equation x_1, x_2 and x_3 represent the accelerating stresses. Regression equations of this type were prepared for the Weibull shape parameter, characteristic life and logarithm of the scale parameter. They could be prepared for any desired reliability characteristic of the parts under test.

The general test method has been used on two different relay types. The most notable success was when it was repeated a second time on Struthers-Dunn FC-215 type relays. Very similar results were obtained in both test programs. On other relay types different regression equations were generated but the same general statistical model and methods were used in developing the equations.

Response surface curves have been prepared for the Struthers-Dunn relays and from them one can estimate the Weibull parameters for any combination of stress levels that are feasible.

The overall method looks promising for use as an ALT and additional work is under way to extend its use to other part types.

It does suffer from some of the disadvantages encountered by other developers of ALT methods however. For example, when a sample of parts are placed on test at a given combination of stresses there are apt to be some parts that either fail early or live extremely long thus causing difficulty in estimating the Weibull parameters of that cell. The response surface curves should only be used within the ranges of the stresses for which they were developed empirically. Any extrapolation outside these limits involves the normal risk of extrapolation error.

The methodology appears to hold promise since it is based on the characteristics of the failure distribution of the parts being tested and the magnitude of the effect of the individual and combined accelerating stresses.

3.0 Advances in Life Testing
3.2 The Multiple Modes of Failure Problem

3.2.1 COMPETING RISKS MODEL

The competing risks failure model provides a statistical explanation of data with more than one mode of failure and also sheds light on the problem of changing failure modes.

One of the "accepted" facts of accelerated life testing is that if there exist failure mode changes from accelerated to normal conditions or vice versa, then the accelerated test is not valid. The validity of extrapolation from accelerated to normal conditions in the face of changing failure modes depends on several things. In order to investigate the nature of the validity of an accelerated test in the face of changing failure modes, it is necessary to have a statistical model for failure times. A question which arises immediately is: In the so often occurring situation of several modes of failure why does failure data frequently fit known distributions, e.g., exponential, Weibull? Since it is unlikely that each mode of K possible modes has the same failure distribution, why are good fits often obtained? The competing risks (CR) model provides a simple and useful explanation of the above point. The CR model is:

Suppose, as a part life time (operation) begins, K mode lifetimes begin, independently; then the mode with the shortest life time (for this particular part) is the cause of failure and the part life is given by

$$X = \text{Min}\,(X_1, X_2, \text{---}, X_K) \qquad (1)$$

where, of course, it is immaterial that only one (the shortest) of the X_i is observable at a time. In general, the d.f.'s $F_{X_i}(x)$ are not identical and need not even be from the same family. In any case, the d.f. of X defined by Equation (1) is

$$F_X(x) = 1 - \prod_{i=1}^{K} \left(1 - F_{X_i}(x)\right) \qquad (2)$$

Now suppose all K modes are exponential but with possibly differing λ's, i.e.,

$$F_{X_i}(x) = 1 - e^{-\lambda_i x}$$

Then from (2)

$$F_X(x) = 1 - e^{-x \sum^{K} \lambda_i}$$

and $F_X(x)$ is again exponential with failure rate $\lambda = \sum^{K} \lambda_i$. Thus for $K > 1$ modes of failure and each mode exponential one must necessarily (if the CR model holds) observe an exponential distribution. Thus, in the face of multiple modes of failure the observance of expoential failure times is well explained by the CR model. If, in practice, the failure mode is identifiable for each failure the λ_i are readily estimated (see handbook). If the failure modes are not identifiable, techniques are not available to estimate the λ_i but $\lambda = \sum^{K} \lambda_i$ can always be estimated by well known methods. It is important to note that, irrespective of whether the modes are identifiable or not, the failure distributions $F_{X_i}(x)$ are unobservable. What is observable is $F_{X_i}(x \mid x_i < x_j \text{ all } i \neq j)$. That is every lifetime (due to mode i) is conditioned on the fact mode i "beat out" the other K-1 modes.

Now, suppose a CR exponential model and that under accelerated conditions

$$\lambda_A = \lambda_{A,1} + \lambda_{A,2} + \text{---} + \lambda_{A,K_A}$$

and under normal conditions (3)

$$\lambda_N = \lambda_{N,1} + \lambda_{N,2} + \text{---} + \lambda_{N,K_N}$$

where $K_N \neq K_A$. It may also be true that $\lambda_{A,i} \neq \lambda_{N,i}$. It is clear from (3) and the discussion of time transformation functions (TTF) that as long as the relationship between λ_A and λ_N persists i.e., their compositions each remain about the same an accelerated test is always valid if it seeks to estimate λ_N from λ_A. However, if it is the purpose to estimate some $\lambda_{i,N}$ from an accelerated test then of course that λ_i must be present in the accelerated test. It is of no particular consequence that $\lambda_{i,A} \neq \lambda_{i,N}$ as long as $\lambda_{i,A}$ is not too close to zero. The CR results are easily extended to the case of each mode being Weibull with all modes having different α's but equal β's. This is done in the handbook.

By far the most interesting case, however, is when

$$F_{X_i}(x) = 1 - e^{-\frac{x^{\beta_i}}{\alpha_i}} \text{ so that}$$

$$F_X(x) = 1 - e^{-\sum^{K} \frac{x^{\beta_i}}{\alpha_i}} \qquad (4)$$

The d.f. given in (4) is definitely not a Weibull distribution. This distribution was studied in some detail for K = 2 (the d.f. (4) is of course the distribution of the first order statistic in a sample of size K, one from each of K Weibulls). It turns out that for K = 2 the d.f. of (4) looks very much like an ordinary Weibull. So much in fact that thousands of samples would be necessary to distinguish (4) from an ordinary Weibull. The point being made here is that possibly many Weibull fits have really been CR Weibulls.

In the general case the F_{X_i} may even be from different families. However, even if the situation is as depicted in (4) the problems of estimating the pairs (α_i, β_i) remains essentially unsolved though if the CR looks like an ordinary Weibull it may suffice as a descriptor. Beside the need for additional research in estimating the parameters of the CR model, it would be interesting to take some data which does not fit any known distribution and try some CR models (perhaps, from different families) on it. The fact that in general the CR model d.f. is not available in closed form need not be an overwhelming limitation because computers are often available. However, tractable or not the CR mode would seem to be a good explanation of failure distributions in the face of multiple modes of failure.

3.2.4 MIXED POPULATION MODEL

The Mixed Population (MP) model is not as intuitively appealing as the CR model but it can explain ill-fitting data quite well in the multiple modes of failure situation.

The MP model is, like the CR model, a physical/statistical explanation of failure times in the face of many modes of failure. It is covered in some detail in the Handbook. Suffice to say here that it assumes each particular part is predestined (a priori) to one and only one of the K possible modes of failure. It is as if K boxes (each containing parts) each labeled a certain failure mode were available and parts are drawn according to some probability law

$$P\ (\text{draw for Box } i) = p_i; \quad \sum_{i=1}^{K} p_i = 1$$

from the boxes. The d. f. of failure times is then

$$F_X(x) = \sum_{i=1}^{K} p_i\, F_{X_i}(x) \tag{1}$$

where $F_{X_i}(x)$ is the failure distribution of mode i failure times. The MP model does not seem to be as intuitively appealing as the CR model since it seems difficult to understand why all K modes cannot (as in the CR model) have a chance to be the "killer" on each and every part. However, the MP model has one decidedly distinct advantage over the CR model of an operational nature:

If the failure modes are identifiable then the $F_{X_i}(x)$ can be readily observed and the parameters of $F_{X_i}(x)$ and the p_i can be estimated. The p_i are easily estimated by taking the fraction of mode i failures to total observed failures. In the CR model the $F_{X_i}(x)$ are never observable whether the failure modes are identifiable or not.

Reference 185 contains an example of estimating MP parameters for $F_{X_i}(x)$ from the Weibull family. If the failure modes are not identifiable then the estimation problem needs much more work. (Reference 185 gives graphic methods.)

The MP model has another advantage over the CR model: for $F_{X_i}(x)$ from exponential/Weibull families (with possibly differing parameters for each of the K modes) the MP model tends to "look worse" on Weibull paper and thus explains ill-fitting (on Weibull paper) data better. An example of this is seen on the facing figure. The MP model of the figure is

$$F_X(x) = 0.3\ (1-e^{-0.05x^2}) + 0.7\ (1-e^{-0.08x^3})$$

i.e.,

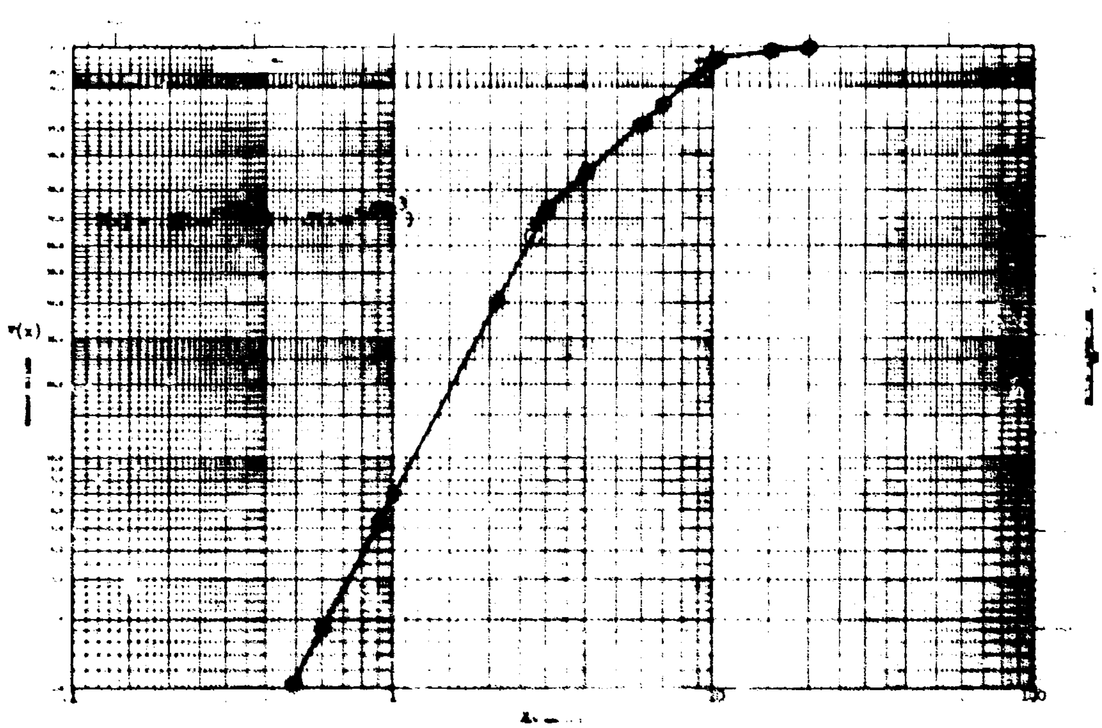
$$F_{X_i}(x) = 1 - e^{-\alpha_i x^{\beta_i}}$$

$\alpha_1 = 0.05 \qquad \alpha_2 = 0.08$

$\beta_1 = 2 \qquad \beta_2 = 3$

$p_1 = 0.3 \qquad p_2 = 0.7$

The usual notation for the scale parameter of the Wiebull is α_i^{-1} but for notational convenience it is called α_i here. These same parameters for the CR model looked very much like an ordinary Weibull (see 6.2.3 Handbook) but it is clear this MP model would not usually (or at least as often as the CR example) be mistaken for an ordinary Weibull. Thus the MP model explains "bad data" somewhat better than the CR model.



3.0 Advances in Life Testing
3.3 Statistical Methods

3.3.1 BAYES METHODS

Bayes sampling plans, when practical, offer the possibility of reducing test time because they provide for the incorporation of prior reliability knowledge into the testing procedure.

The rather detailed literature search (conducted for the handbook) for more powerful statistical methods of testing showed clearly that, irrespective of whether Bayes sampling plans will become popular in the immediate future, a great deal of research in Bayes reliability test plans is going on. The reason is not hard to find. If a prior distribution on reliability exists and it is reasonably "good" with respect to the reliability desired then test time may be reduced.

Actually the movement toward Bayes plans is just a part of a great deal of research being conducted in the general area of decision theory. There are many who argue that, quite aside from reduction in time/costs considerations, if a prior distribution exists then any decision procedure selected must take into account the prior distribution. Here, of course, lies the great stumbling block for Bayes methods: determining the prior distribution. There has been little done in this regard in Reliability. It is mandatory that this research (discovering the prior distribution) begin before Bayes methods can be used. Another important area of research is the robustness of the Bayes procedures. If the procedures are (relatively) insensitive to departures from the exact prior, this would be nice to know. In fact, most of the Bayes research in Reliability consists of the "arithmetic" of the results for postulated priors. Because of the involvement of the prior many of the problems become intractable quite rapidly and it is common to see in the (Reliability) Bayes literature some assumptions of a questionable nature. Perhaps, the best example (it occurred two or three times in the literature) is the selection of a two (2) point prior distribution. For example, suppose reliability is measured by MTBF(θ). It is often assumed the prior distribution is

$$P(\theta_0) = p \qquad p + q = 1 \qquad P(\theta_1) = q \tag{1}$$

That is, only two values of θ (namely θ_0, θ_1) can occur. This is an extremely disconcerting practice; particularly, when computers are available to solve intractable problems.

Another discouraging practice, although it was noticed very little in the literature search, is the idea that everyone is entitled to their opinion about the form of the prior distribution. Roughly speaking, the procedure implies one can sit at the desk and determine a prior and use it. This procedure is ill-considered unless a great deal of positive results are available concerning robustness of the procedures.

The decision-theoretic people have more or less settled on costs as the ultimate criteria for designing decision procedures (e.g., reliability demonstration tests). However, the literature search in reliability shows that the Bayes methods being developed are leaning (thus far) quite heavily in the direction of the posterior risks. For this reason, they will be explained in some detail here. It was previously pointed out that the test plans today are selected so that ($\theta_0 > \theta_1$)

$$P\ (\text{Acceptance} \mid \theta_1) = \beta = \text{consumer's risk}$$

$$P\ (\text{Rejection} \mid \theta_0) = \alpha = \text{producer's risk} \qquad (2)$$

where α and β are small. The numbers β and $(1 - \alpha)$ are points on the usual O.C. curve. The posterior risks involve turning these probabilities "around" in a sense

$$P\ (\theta \leq \theta_1 \mid \text{Acceptance}) = \text{posterior consumer's risk}$$

$$P\ (\theta \geq \theta_0 \mid \text{Rejection}) = \text{posterior producer's risk} \qquad (3)$$

It will be noticed that in (3) $P(\theta \mid \text{Acceptance})$ and $P(\theta \mid \text{Rejection})$ are actually probability distributions whereas, (2) is not. When the posterior risks are written as in (3) they are often called Bayes confidence limits (conditioned by acceptance or rejection of course). In the case of (3), θ_1 is a lower confidence limit and θ_0 is an upper confidence. It should also be noted the Bayes confidence limits of (3) are a true probability statement rather than the inductive classical confidence limits (see Introduction to Bayes Methods 5.1 of the Handbook). In any case, the specification of the four tuple (θ_0, θ_1, posterior producers and posterior consumer's risks) can lead to a demonstration test.

The actual calculation of Bayes confidence limits is straightforward enough (given the prior distribution is available). Suppose MTBF (θ) is the reliability parameter of interest and that it has prior p.d.f. $f(\theta)$. Suppose further that, given θ, the distribution of failure times t is $g(t \mid \theta)$.

Then the conditional distribution of θ having observed, for example, one random life time is

$$h\ (\theta \mid t) = \frac{f(\theta) g(t \mid \theta)}{\int_{\theta} f(\theta) g(t \mid \theta) d\theta} \qquad (4)$$

and selecting some θ_* for a lower confidence limit:

$$P\ (\theta \geq \theta_* \mid t) = \int_{\theta_*}^{\infty} h\ (\theta \mid t)\ d\theta = \frac{\int_{\theta_*}^{\infty} f\ (\theta)\ g\ (t \mid \theta)\ d\theta}{\int_{\theta} f\ (\theta)\ g\ (t \mid \theta)\ d\theta} \qquad (5)$$

(5) is easily extended for several life times available, i.e., t_1, t_2, ..., t_K. Conversely, one may preselect the right hand side in (5) and solve for θ_*.

The Bayes research, in Reliability at least, seems to have reached the point of fitting some prior distributions and showing that the Bayes procedures can be of service.

3.3.2 ADVANCES IN DISTRIBUTION DEPENDENT METHODS

More powerful methods of estimating the reliability related statistics of the Weibull and gamma distributions based on life tests are now available. The above distributions are now widely used as distributions of life because they allow for monotone (increasing or decreasing) as well as constant failures rates.

To obtain realistic representations of the distribution of life times, it is necessary to utilize distribution functions that allow monotone (increasing and decreasing) as well as constant failure rates. Monotone increasing failure rates give a better representation of life times when parts are in a wear out phase. Mechanical and electromechanical parts appear to exhibit wear out during all phases of life. Some electronic parts appear to have wear out phases after long phases of constant failure rate. Monotone decreasing failure rates describe systems undergoing debugging and also entire lots of solid state electronic parts. Looking at an entire lot of devices the failure rate of the lot decreases in the beginning as inherently deficient parts are weeded out.

The Weibull and gamma distributions are both able to represent distributions of life times with monotone failure rates. The Weibull distribution written as

$$F(t) = 1 - \exp(-t^{\beta}/\alpha) \qquad \alpha, \beta, t>0$$

$$= 0 \qquad \text{elsewhere}$$

has monotone decreasing failure rate for $\beta < 1$, monotone increasing failure rate for $\beta > 1$ and reduces to the exponential for $\beta = 1$. α is the scale and β is the shape parameter. The gamma density written as

$$f(t) = \frac{1}{\Gamma(K)m} \left(\frac{t}{m}\right)^{K-1} \exp(-t/m) \qquad m, K, t>0$$

$$= 0 \qquad \text{elsewhere}$$

has monotone decreasing failure rate for $K < 1$, monotone increasing for $K > 1$. The gamma also reduces to the exponential when $K = 1$. m is the scale and K is the shape parameter.

Reliability, the probability that a part survives for a time, mean life, and the percentiles of the life time distribution are reliability related statistics. These reliability

related statistics are functions of the parameters of the distribution of life times. Thus when the distribution is gamma with parameters m and K the mean life E(t) is equal to (Km). Consequently, statistical methods may estimate the reliability related statistics per se or the parameters of the distribution functions. *

The ATT handbook contains methods for finding the reliability statistics when the distribution of life times is either Weibull or gamma in Section 5.2. The table on the facing page summarizes the methods presented. The first column shows the statistic estimated. The property of the estimator (maximum likelihood, minimum variance unbiased, etc.) are presented in the second column. The last columns show the data requirements. They indicate if censored data can be handled, if the data must be ordered, and what specific order statistics are necessary.

The methods presented in the ATT handbook and summarized in the table are sufficient to allow the use of the Weibull and/or gamma distributions in life testing analysis. The ability to use these distributions is a significant step forward since it makes possible the representation of monotone failure rates.

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* When the distribution of life times is exponential,

$$F(t) = 1 - \exp(-t/\theta) \qquad t, \theta > 0$$

$$= 0 \qquad \text{elsewhere}$$

the parameter θ is the mean life and therefore θ is both a parameter and a reliability related statistic.

3.0 Advances in Life Testing

3.3 Statistical Methods

3.3.2 ADVANCES IN DISTRIBUTION DEPENDENT METHODS (Continued)

TABLE 3.3.2. METHODS OF ESTIMATING RELIABILITY STATISTICS FROM WEIBULL AND GAMMA DISTRIBUTIONS

	Weibull Distribution		
Method No.	Statistic Estimated	Property of Estimator	Data Requirements
5.2.1	scale parameter shape parameter	Asymptotically Normal and Unbiased	Sample of n lifetimes.
5.2.2	scale parameter	Asymptotically Normal and Unbiased	Order statistics from a sample of n life times. Only two actual values need be known.
5.2.3	scale parameter	Max. Likelihood or Unbiased Estimate	Value of first m of n order statistics. The data may be censored. Shape parameter must be known.
5.2.4	shape parameter	Unknown	First two order statistics (scale parameter need not be known).
5.2.5	scale parameter	Unknown	Any order statistic. Censored data is permissible.
5.2.6	confidence limits on percentiles	Unknown	Value of any order statistic censored data permissible.
5.2.7	percentiles; confidence limits on percentiles	Asymptotically unbiased	Censored data is acceptable ordered sample is required.
5.2.8	percentiles; confidence limits on percentiles	Linear Invariant Minimum Variance, Biased, Asymptotically Normal	Censored data is acceptable ordered sample is required.
5.2.9	percentiles; confidence limits on percentiles	Unknown	Complete sample of n life times.
5.2.10	Reliability Confidence Bound	Asymptotically efficient	Complete ordered sample
5.2.11	Reliability Confidence Bound	Unknown	First and last order statistic of the sample. Number in the sample exceeding critical time.

TABLE 3.3.2. METHODS OF ESTIMATING RELIABILITY STATISTICS FROM WEIBULL AND GAMMA DISTRIBUTIONS (Continued)

Gamma Distribution			
Method No.	Statistic Estimated	Property of Estimator	Data Requirements
5.2.16	scale parameter shape parameter location parameter	Max likelihood	First M of N order statistics of the sample. Censored data is permissible.
5.2.17	scale parameter	unbiased	Value of one order statistic from the sample.

3.3.3 ADVANCES IN DISTRIBUTION FREE METHODS

Distribution free methods of estimating reliability related statistics are now available for distributions where all that is known is that the failure rate is monotone (increasing or decreasing).

Distribution free (sometimes called nonparametric) methods, can always be applied to estimating reliability related statistics of a distribution of life times. Unfortunately, estimates made by these methods are usually quite inefficient. A basic understanding of distribution free methods can be obtained from Chapter 16 of: Mood, A. M. Introduction to the Theory of Statistics, McGraw Hill, 1950.

The efficiency can be improved if the failure rate is known to be monotone increasing (or decreasing) even if no other assumptions are made. The ATT handbook contains methods for (1) determining if the distribution has a monotone failure rate and (2) for estimating:

2.1 Reliability for a specified time.
2.2 Confidence bounds on Reliability.
2.3 Limiting failure rate following debugging.

Estimates 2.1 and 2.2 can be obtained from either attribute (number of parts surviving for the critical time) or parameter (actual failure time) data. Ordering of the sample results is required but the computations are not difficult. 2.3 requires failure times. These estimates are maximum likelihood although they do not have all the properties that distribution dependent maximum likelihood estimators possess.

Another method determines the sample size required to test the value of the quantiles of the life time distribution given that the failure rate is monotone (increasing or decreasing).

These new distribution free methods are powerful compared to older distribution free methods but are still inefficient compared to distribution dependent methods.

4.0 Conclusions

Over 500 technical reports were studied in detail to establish both the state of the art and potential advances of methods for reducing test times, expenses, and sample sizes.

The following is a summary of the conclusions of the findings of this study:

- The major efforts in developing ALT methods have been concentrated on electronic parts with a lesser effort on mechanical parts. Very little has been done on a system level.

- None of the traditional ALT methods have been fully validated.

- Generally, the statistical approach in the development of ALT methods was weak. In many cases, sample sizes were too small to yield statistical significance, there were insufficient points to fit regression lines, confidence limits were used infrequently and all too frequently the assumption of an exponential distribution of failure times was used when it was not validated.

- Attempts at validation of a given ALT method were not usually apparent. Frequently an ALT method was described, the test results(or part of them) were given, and nothing more was added to prove the validity of the method. Little use was made of the validation methods discussed in Section 2 of the Handbook of ALT Methods.

- Where promising ALT methods were developed as in the case of the transformation models and the regression models the range of applicability is fairly restricted. This is so mainly because these methods have not been applied beyond relays and switches as yet.

The more powerful statistical methods literature search brought to light the following facts:

- The statistical problem of reducing reliability test time/costs is receiving a great deal of competent attention.

  Methods are being developed along two lines

  i) the most efficient methods without the use of prior information.
  ii) the most efficient methods using prior (Bayes) information.

- The Weibull and gamma distributions have received a great deal of attention, and rightfully so because of their flexibility, and may well replace the exponential in "popularity" in the future.

- A number of distribution free methods have been developed. Their efficiency can be improved by stipulating if the failure rate is monotone increasing/decreasing.

- A mechanism is needed to reduce the lag between the development of more powerful statistical methods and their adoption by the Engineering discipline.
- In general, statistical methods are very sensitive (efficiency wise) to the assumptions made. More work is necessary in validating the assumptions.

Multiple Modes of Failure Problem

- This subject has received relatively little of the attention it needs. The multiple modes of failure problem needs attention because it has a great deal to do with the validation of and insight into accelerated life tests.
- A promising model, the CR model, exists to explain failure data in the face of multiple modes of failure.
- An additional model, the MP model, exists which though not quite as appealing as the CR model, can also help validate and provide insight into accelerated tests.
- Some model of the multiple modes of failure problem is required in order for part improvement programs to be conducted in good statistical fashion.

5.0 Recommendations

Since none of the traditional ALT methods has been validated it would appear that the significant advances in the field will be made as a result of further development of transformation models, regression models and more powerful statistical methods.

The following recommendations are presented as a result of the findings of this study:

- The use of the transformation models should be extended to parts other than relays and switches.

- The use of regression models employing central composite designs should be extended to parts other than relays.

- The Arrhenius and Eyring Models, step stress testing, progressive stress testing and inverse power rule should be checked for validation using historical data and the improved validation methods of Section 2 of the Handbook of ALT Methods.

Regarding statistical methods, the recommendations are:

- Further study to refine the CR and MP models for the multiple modes of failure problem; in particular estimation of parameters.

- Research into the types of prior distribution encountered in Reliability practice so that Bayes methods may be wisely and usefully applied.

- Develop methods of cutting down the time lag between the development of good methods of reducing test time and costs and their adoption. The Handbook should help somewhat.

- Develop standard methods and tables (under one cover) for the (ever increasing in popularity) Weibull and Gamma distribution.

Section 6

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UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Hughes Aircraft Co. Ground Systems Group Fullerton CA	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP N/A

3. REPORT TITLE

ACCELERATED TESTING TECHNOLOGY

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report, Feb 1966 to Jul 1967

5. AUTHOR(S) (First name, middle initial, last name)

Yurkowsky, W. Finkelstein, J. M.
Schafer, R. E.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
November 1967	420	524

8a. CONTRACT OR GRANT NO. AF30(602)-4046 b. PROJECT NO. 5519 c. Task 551902 d.	9a. ORIGINATOR'S REPORT NUMBER(S) FR 67-16-157 FR 67-16-185 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) RADC-TR-67-420, Vols. I & II

10. DISTRIBUTION STATEMENT

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with the prior approval of RADC (EMERR) GAFB NY 13440.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
Donald W. Fulton, Project Engineer (EMERR)	Rome Air Development Center (EMERR) Griffiss AFB NY 13440

13. ABSTRACT

This report, in two volumes, is devoted to an investigation into the state-of-the-art of methods for reducing the time and expense associated with life testing, particularly as it relates to parts. The areas investigated are divided into accelerated testing and more powerful statistics. The accelerated tests treated in the report are tests at stresses higher than nominal design levels applied either singly or in combinations at constant, progressively increasing, or increasing by steps, stress levels. The more powerful statistical approaches found to be pertinent are those using prior information distribution-dependent methods and distribution-free methods.

Volume one of this report, prepared in handbook format, gives an assessment of advantages and limitations of the present available methods for reducing test time and expenses and presents in compact, but complete form, the instructions for using the methods which represent the state-of-the-art of accelerated life testing.

Volume two presents the methodology used in performing the study, explains the evaluation systems used on the methods reported in the literature, establishes the criteria for inclusion of a method in Volume one, and highlights to useful methods developed as well as those which show promise for future development.

DD FORM 1 NOV 65 1473

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Accelerated Testing						
Reliability Demonstration						
Statistics						

UNCLASSIFIED
Security Classification